JSC-07636

SPACE SHUTTLE
LIGHTNING PROTECTION CRITERIA DOCUMENT

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National Aeronautics and Space Administration

LYNDON B. JOHNSON SPACE CENTER

Houston, Texas

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SPACE SHUTTLE
LIGHTNING PROTECTION CRITERIA DOCUMENT

PREPARED BY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS
September 11, 1973

PREFACE

Revisions to this document after the issue of the baseline document are typed in italics.

Many terms in this document have special meanings which may be different from those normally understood, consequently a glossary of terms is provided.

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1.0 INTRODUCTION

The Space Shuttle vehicle may experience lightning in flight even though launch restrictions will be imposed. In addition, the system will be exposed to lightning on the ground and possibly during other mission phases.

The Space Shuttle system, including the vehicle and all facilities where major tests or operations are performed, shall be designed to accept the lightning flash, as defined in this document, directly to the system during either preflight or inflight operations without affecting any equipment in such a manner as to endanger personnel safety, mission success, or to delay a launch.

This document defines the lightning environment for design and imposes the requirements that the design must satisfy to insure the protection of the Space Shuttle vehicle system from the direct and indirect effects of lightning. Specifications, criteria, and guidelines included in this document provide a practical and logical approach to the protection problems.

Protection against the indirect effects of lightning is intimately involved with the electromagnetic compatibility and electromagnetic interference functions. While this document does not deal specifically with electromagnetic compatibility and electromagnetic interference, it does deal with the interactions between lightning protection measures and measures employed for electromagnetic compatibility and control of electromagnetic interference.

In cases of conflict between the contents of this document and other specifications or criteria relating to lightning protection, this document shall govern. Deviations shall be granted only upon the concurrence of the Lightning Protection Committee and the approval of the Space Shuttle Configuration Control Board Level II.

The words may, shall, and should have a specific meaning in this document. See glossary of terms for definition.

1.1 CHANGE PROCEDURE

Delegated representatives of the National Aeronautics and Space Administration; Johnson Space Center, Marshall Space

Flight Center, Kennedy Space Center; United States Air Force Space and Missile Systems organization (XRZ); and Rockwell International shall be points of contact for proposed changes through the Lightning Protection Committee. Figure 1-1 is a listing of authorized representatives and figure 1-2 is a sample of the required amendment form.

After Lightning Protection Committee coordination, all proposed changes shall be prepared and processed in accordance with the Space Shuttle program level II Configuration Management Requirements document, JSC-07700, Volume IV.

1.2 DEVIATION PROCEDURE

Deviations and waivers to the requirements of this document shall be submitted for approval in accordance with the Space Shuttle program level II Configuration Management Requirements document, JSC-07700, Volume IV.

AUTHORIZED REPRESENTATIVES

FOR

LIGHTNING CRITERIA DOCUMENT CHANGE COORDINATION

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ROCKWELL INTERNATIONAL

George Lindewall
Nathan Scott

Figure 1-1.- Authorized representatives for document change coordination.

AMENDMENT
SPACE SHUTTLE LIGHTNING
PROTECTION CRITERIA DOCUMENT

NUMBER

DATE

PROPOSED CHANGE

REASON FOR CHANGE

CONCURRENCE

_____ Johnson Space Center

_____ Kennedy Space Center

_____ Marshall Space Flight Center

_____ Space and Missile Systems Organization-XRZ (USAF)

_____ Rockwell International

APPROVAL _____

JSC Form 1455 (May 73) NASA-JSC

Figure 1-2.- Sample amendment form.

2.0 LIGHTNING ENVIRONMENT

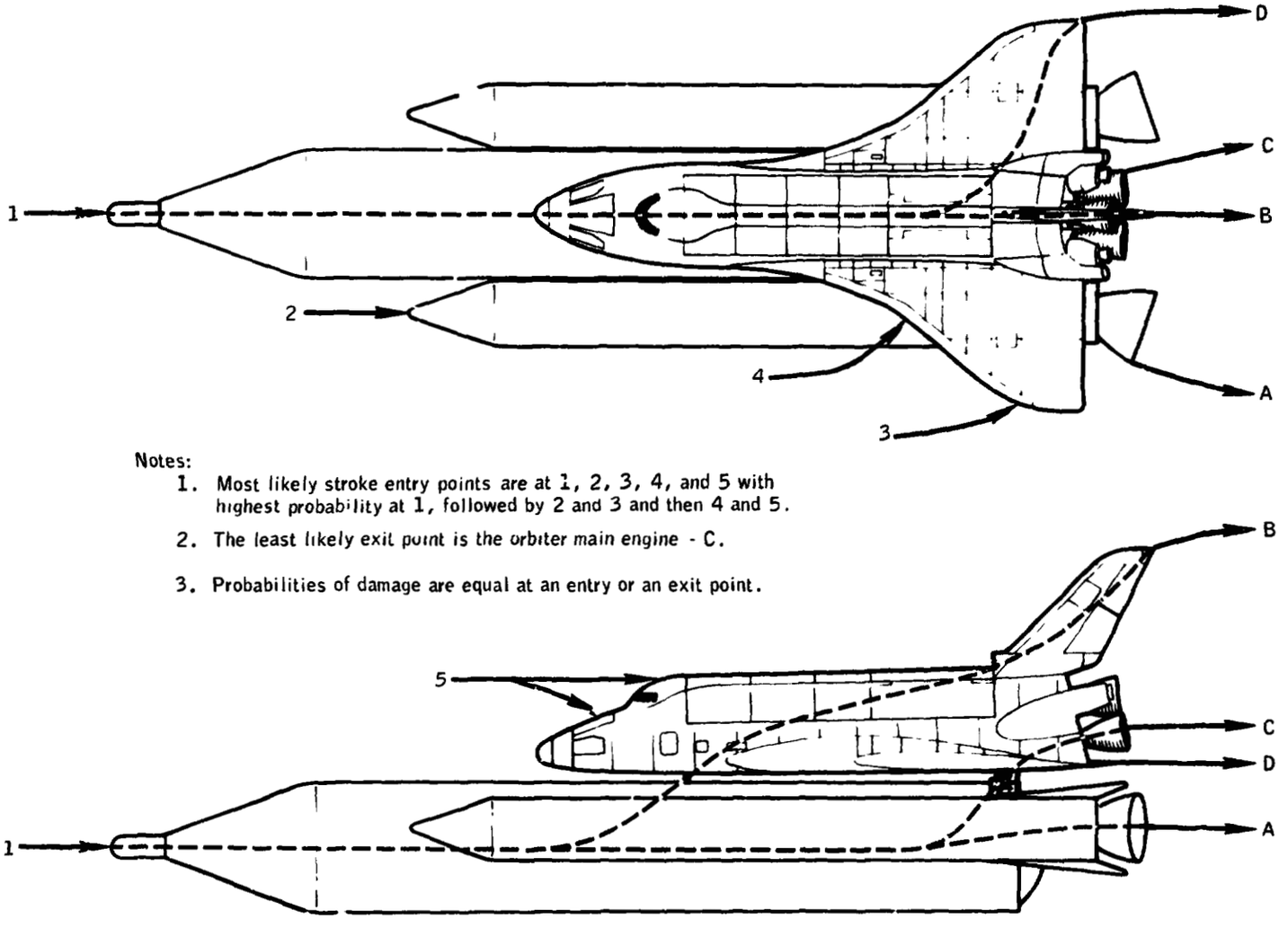
The model lightning flash shown in figure A-1 and detailed in Appendix A shall be used for analytical and test purposes to the degree practical.

This model involves two strokes: the first has a current peak of 200 000 amperes and a current rate of change of 100 000 amperes per microsecond (100 KA/10^{-6} sec); the second stroke is half the magnitude of the first. The model incorporates intermediate currents of several thousand amperes persisting for a few milliseconds, and a continuing current, comprised of two phases, of 700 amperes average for 50 milliseconds succeeded by 400 amperes for 300 milliseconds. The total charge transfer in the model is 200 coulombs, 155 coulombs of which passes in the continuing current.

Only rarely can laboratory tests duplicate the severity of the model flash. Simulation of the effects of the severe flash are most practically made using several different test waveforms, each tailored to duplicate one of the effects of the entire severe lightning flash. Section 7 and Appendix E describe the desirable characteristics of test waveforms to be used.

2.1 LIGHTNING ENTRY/EXIT POINTS (LAUNCH AND DESCENT PHASES)

2.1.1 The most likely lightning entry/exit points for the launch phase and the descent phase are shown in figures 2-1 and 2-2, respectively.



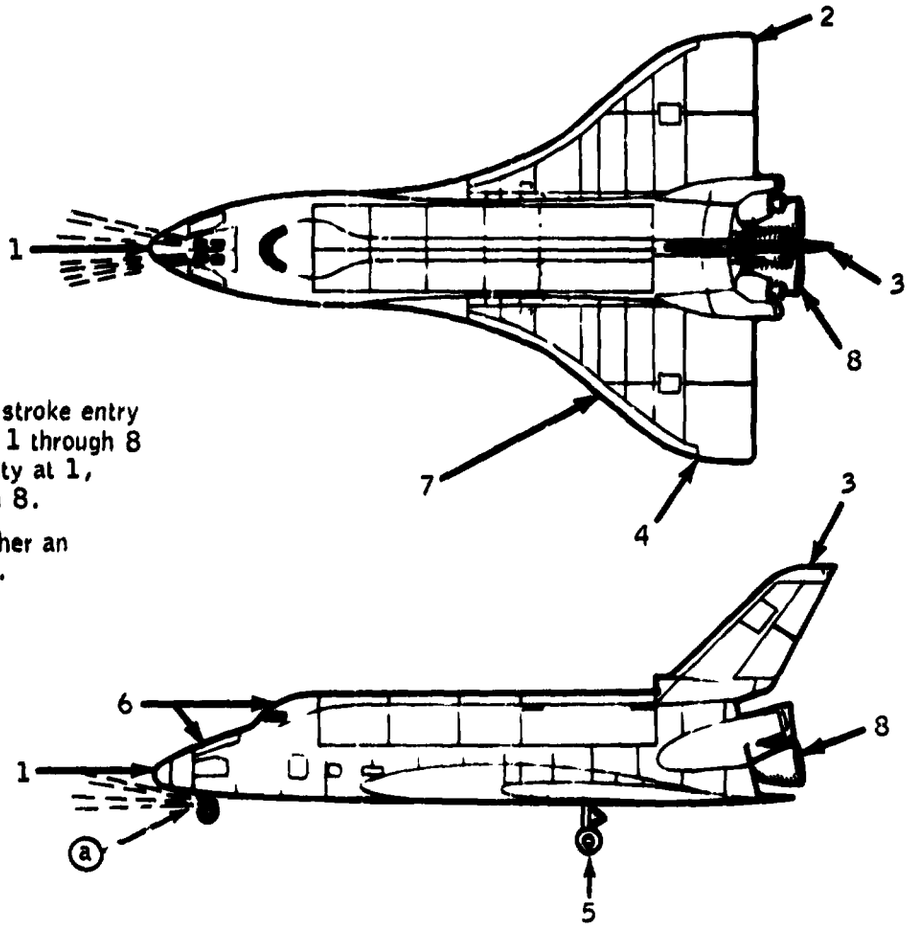
Notes:

1. Most likely stroke entry points are at 1, 2, 3, 4, and 5 with highest probability at 1, followed by 2 and 3 and then 4 and 5.
2. The least likely exit point is the orbiter main engine - C.
3. Probabilities of damage are equal at an entry or an exit point.

Figure 2-1.- Anticipated lightning stroke entry and exit points for composite shuttle vehicle during the launch phase.

External lighting

ⓐ Landing



Notes:

1. Most likely lightning stroke entry and exit points are at 1 through 8 with highest probability at 1, followed by 2 through 8.
2. Each point can be either an entry or an exit point.

Figure 2-2.- Anticipated lightning stroke entry and exit points for orbiter descent phase.

3.0 FLIGHT HARDWARE

3.1 DIRECT EFFECTS

Direct effects of lightning are the burning, blasting, direct coupling of voltages and currents, and structural deformation caused by lightning arc attachment, as well as the high-pressure shockwaves and magnetic forces produced by the associated high currents.

3.1.1 Electrical Cables

Electrical cables should not, where possible, be exposed to the direct effects of lightning. Exposed cables shall be covered with metallic enclosures.

3.1.2 Vehicle Structural Interfaces (Orbiter/External Tank/Solid Rocket Booster)

Each interface shall be able to withstand the model lightning flash without jeopardizing the strength or any functions required to safely continue the mission.

Structural interface surfaces shall be designed to have less than 2.5 milliohms resistance across their mated surfaces. The interface shall also retain the specified resistance for the useful life of the vehicle.

3.1.3 Bonding

An electrical path shall be provided between structures or components that are in the main lightning current path and shall have a resistance of 2.5 milliohms or less. Only those doors, panels, and control surfaces in the main lightning path require bonding. However, bonding of external doors, panels, and control surfaces not in the main lightning path shall have a resistance of not more than 10 milliohms unless electromagnetic interference considerations dictate a lower resistance. Electrical cables and connectors are excluded from the requirements of this paragraph.

3.1.4 Structure

3.1.4.1 For ground operations, a preferred continuous metallic path shall be provided from the preferred point of lightning entry into the composite Space Shuttle vehicle to the preferred exit point. The metal shall be capable of conducting the peak and

continuous current of the model lightning flash without jeopardizing crew safety or delaying a launch.

3.1.4.2 Vehicle extremities, both metallic and non-metallic, shall withstand the full model lightning flash without sustaining damage that would cause a malfunction that would result in the loss of the vehicle. Non-metallic surfaces shall either be supplied with exterior current-conducting paths, or shall demonstrate the intrinsic capability to withstand the lightning flash. Those areas of the vehicle for which the state-of-the-art cannot provide protection shall be tested to determine the operational constraints.

3.1.5 Bearing Assemblies

Each bearing assembly in the main lightning current path shall be able to withstand the model lightning flash without damage. Figure 3-1 shows the hinged bearing surfaces. Continuous metal hinges (piano-type) are self bonding, provided that the resistance across the hinge is less than 10 milliohms.

3.1.6 Antennas

Antennas should not be located in the prime lightning arc attachment areas. See figures 2-1, 2-2, and 6-1. All antennas shall be protected against lightning effects.

3.1.7 Flammable Fluid, Oxygen, and Monopropellant Systems

Tanks, lines, and associated access doors, drains, and vents shall be designed such that sparking from lightning and static electricity cannot occur inside the vehicle structure.

Lines, tanks, drains, and vents exposed to direct lightning arc attachments shall be designed such that the ignition point of either the container materials or the fluids shall not be reached. Refer to Appendix B for guideline data.

3.2 INDIRECT EFFECTS

Indirect effects of lightning are damage or malfunctions due to currents and voltages caused by the electromagnetic fields associated with lightning.

Electrical equipment shall be designed to withstand the electromagnetic effects produced by lightning without damage or malfunction that endangers the crew, the success of the mission, or delays a launch.

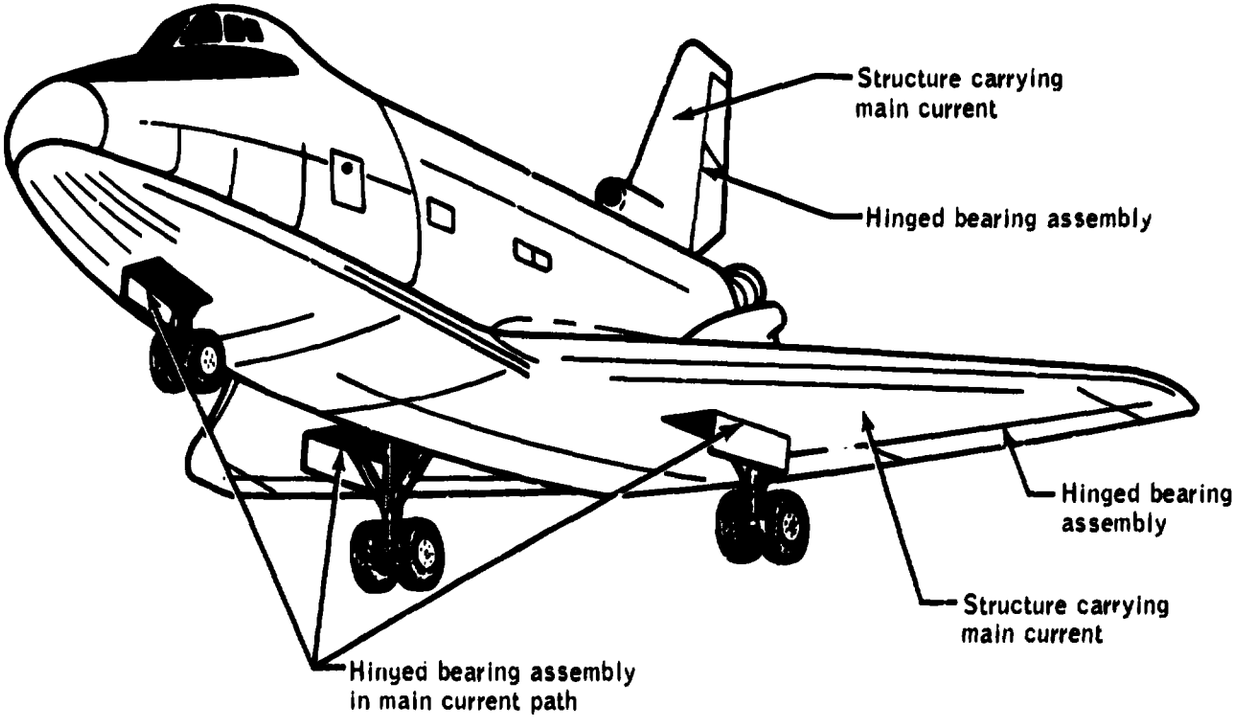


Figure 3.1.- Hinged bearing assemblies versus main current paths.

The electrical equipment should be designed to withstand electromagnetic effects produced by lightning without any malfunction or upset, even if such malfunction does not endanger the crew or the success of the mission.

Compliance to this requirement shall include the interactions between the different terminal equipment or between terminal equipment and interconnecting cables, and shall be demonstrated in each case by analysis or test.

Transient design levels shall be established in accordance with Appendix D.

3.2.1 Shielding

3.2.1.1 Overall shields shall be provided for all cables to control the transients unless:

a. Protection is provided by means other than shields; or

b. Such transients do not affect crew safety, mission success, or time of launch.

Overall cable shields shall be continuous without breaks or splices, except at connectors and at branch points on cables with multiple breakouts. The overall shield, as a minimum, shall be grounded to bulkhead metallic structure or equipment ground at each end. Intermediate grounding may be used.

3.2.1.2 Shields on conductors, where required, shall have a minimum coverage of 85 percent. Shielded conductors inside the overall cable shields may be grounded as appropriate for control of low-level or low-frequency electromagnetic interference.

3.2.1.3 On external skins, termination of the overall shield shall be made along a 360-degree periphery of the connector shell. The connector shell shall be grounded in a 360-degree manner to the surface upon which it is mounted. Termination and grounding of the overall shield at such surfaces with pigtails or single pins shall not be acceptable.

3.2.1.4 Termination of the overall shield at connectors on internal bulkheads should be made along a 360-degree periphery of the connector shell. If termination and grounding is made with a pigtail or through a connector pin, the connection shall be made directly to the bulkhead using the minimum length path. The resistance of the pigtail shall not exceed 2.5 milliohms.

3.2.2 Power Returns

3.2.2.1 Current-conducting paths shall be provided between vehicle interfaces only through the electrical interface. Structure at intervehicular interfaces shall not be relied upon as current-conducting power-return paths.

3.2.2.2 Intravehicular power distribution systems should incorporate a single-point grounding system to prevent ground loops.

3.2.2.3 Floating power distribution systems are acceptable.

3.2.2.4 Intravehicular structural returns are acceptable provided that such paths do not allow coupling that would cause adverse effects[1] to the operation of any system in the vehicle.

3.2.2.5 Electromagnetic coupling can be controlled by shielding, routing of conductors, or by the use of transient suppression devices. All transient suppression device failure modes should be fail-open under normal vehicle system operating conditions and after a lightning strike. (See Appendix C for suppression devices and their capabilities.)

3.2.3 Vehicle Wiring Interfaces (Orbiter/External Tank/Solid Rocket Booster)

Wiring interfaces shall be controlled to prevent voltages or currents, resulting from the direct or indirect effects of lightning, from damaging or interfering with terminal equipment.

3.2.4 Bandwidth Limitations

Equipment frequency bandwidths should be established that are no wider than necessary for proper operation.

3.2.5 Avionics Hardware

Lightning effects shall not cause a loss of power of such a duration that would result in adverse effects to category 1 equipment.

[1]See glossary of terms for definition of adverse effects.

4.0 GROUND HARDWARE

Ground hardware, for the purpose of this document, includes equipment and facilities directly or indirectly connected to the vehicle, the proper function of which is essential to personnel and equipment safety, mission success, and to prevent launch delay.

4.1 DIRECT EFFECTS

Equipment and facilities which cannot withstand direct lightning effects, as defined in paragraph 3.1, shall be protected by air terminals and/or conductors. Equipment and facilities may be protected by the cone of protection of other structures.

4.1.1 Vehicle-to-Facility Grounding

Facility grounding provisions shall be designed to provide a resistance of 2.5 milliohms or less between the external tank and the mobile launcher, between the Orbiter and the mobile launcher, and between each of the solid rocket motors and the mobile launcher.

4.1.2 Electrical Bonding

The electrical conductive path or bond between structures or components in the main lightning current path shall have a resistance of 2.5 milliohms or less.

4.1.3 Cable Trays

All cable trays shall be protected from a direct lightning flash. All vertical cable trays on facility structures exposed to the electromagnetic effects of lightning shall be of solid metal and completely covered, and when practical, be mounted internal to the facility structure.

4.2 INDIRECT EFFECTS

Indirect effects are damage or malfunctions due to currents and voltages caused by the electromagnetic fields associated with lightning.

4.2.1 Grounding

4.2.1.1 Grounding systems, such as E (Equipment) and I (Instrumentation) ground systems, shall be connected together at only a single point, and this single point shall be connected to earth.

4.2.1.2 Circuits and signal ground shall be referenced to a grounding system isolated from structure except at one point.

4.2.2 Lightning Protection Shielding

4.2.2.1 All cables shall have an overall shield for lightning protection. The overall shield, as a minimum, shall be grounded to bulkhead metallic structure or equipment grounding terminals at least at each end. Overall shields shall be continous without breaks or splices except at connectors and at branch points on cables with multiple breakouts. Intermediate grounding should be used where the overall shield penetrates or touches metal. Cables located completely within shielded compartments need not comply.

4.2.2.2 Shields on conductors shall have a minimum coverage of 85 percent. Shielded conductors inside the overall cable shields may be grounded as appropriate for control of low-level or low-frequency electromagnetic interference.

4.2.2.3 Termination of the overall shield on external bulkheads shall be made along a 360-degree periphery of the connector shell. The connector shell shall be grounded in a 360-degree manner to the bulkhead upon which it is mounted. Termination and grounding of the overall shield at such bulkheads with pigtails or single pins shall not be acceptable.

4.2.2.4 Termination of the overall shield at connectors on internal bulkheads should be made along a 360-degree periphery of the connector shell. If termination and grounding is made with a pigtail or through a connector pin, the connection shall be made directly to the bulkhead metallic structure using the minimum length path. The resistance of the pigtail shall not exceed 2.5 milliohms.

4.2.3 Bandwidth Limitations

Equipment frequency bandwidths should be established that are no wider than necessary for proper operations.

4.3 VEHICLE/FACILITY INTERFACES (LOOKING TOWARDS THE FACILITY)

4.3.1 Metallic Tubes and Ducts

All metallic tubes and ducts penetrating the vehicle skin shall be electrically bonded to the vehicle skin. If this bonding is accomplished with a jumper, this jumper shall be as short as possible.

4.3.2 Transient Protection Devices

Transient protection devices shall be installed on power lines at the closest practical point to where the power lines penetrate the vehicle skin. These transient protection devices shall be installed both line-to-line and line-to-ground. Such transient protection devices may be eliminated, if it is shown by analysis and test that the margin between the actual-induced transient levels and the susceptibility of the terminal apparatus meets the guidelines of Appendix D.

4.3.3 Vehicle-to-Ground Hardware Interfaces

Wiring interfaces shall be controlled to prevent voltages or currents resulting from the direct or indirect effects of lightning from damaging or interfering with terminal equipment. At the vertical flight facility, ground hardware electrical lines should interface the vehicle as close to the base as practical to minimize the indirect effects of lightning.

5.0 PYROTECHNICS

5.1 PROTECTION OF MATERIALS AND DEVICES

Installation of pyrotechnic materials and devices shall be designed to provide a specific current path around the pyrotechnic materials and devices such that the effects of the full model lightning current will not cause dudding or inadvertent firings.

5.2 PROTECTION OF ELECTRICAL SYSTEMS

Pyrotechnic electrical firing circuits, power sources, and controlling logic shall be designed such that no functional failures will result from the direct and indirect effects of the full model lightning current.

5.2.1 Bonding

The initiator and controlling logic containers shall be electrically bonded to the vehicle structure. The measured electrical bond resistance from the components to their respective adjacent vehicle structure shall be less than 2.5 milliohms.

5.2.2 Shielding

Shielded twisted-pair wires shall be used for each single bridgewire explosive device initiator. Shields shall be continuous without breaks or splices, with the exception of through-pins in pressure bulkhead electrical connectors. Shielding termination at connectors shall provide 360-degree coverage. The shield design shall provide a minimum area coverage of 85 percent for attenuation.

5.3 TESTING

The requirements of paragraphs 5.1 and 5.2 shall be verified by tests.

6.0 FERRYING REQUIREMENTS

6.1 AIR-BREATHING ENGINES

Air-breathing engines, nacelles, and pylons shall be designed to provide a direct current-carrying path to the vehicle basic structure such that the full model lightning current will not cause engine malfunction due to physical damage or induced electromagnetic effects.

6.2 EXTERIOR LIGHTS

All exterior lights shall have their metallic bases electrically bonded to the vehicle basic structure to provide a direct lightning strike current path. The light design shall insure lightning flashover to the basic structure and provide protection from transient voltages being induced into the vehicle electrical system.

6.3 PITOT TUBES

Pitot tubes shall be designed to prevent the lightning current from directly coupling into the vehicle electrical power system, and/or damaging the vehicle structure.

6.4 LIGHTNING ENTRY/EXIT POINTS (FERRY PHASE)

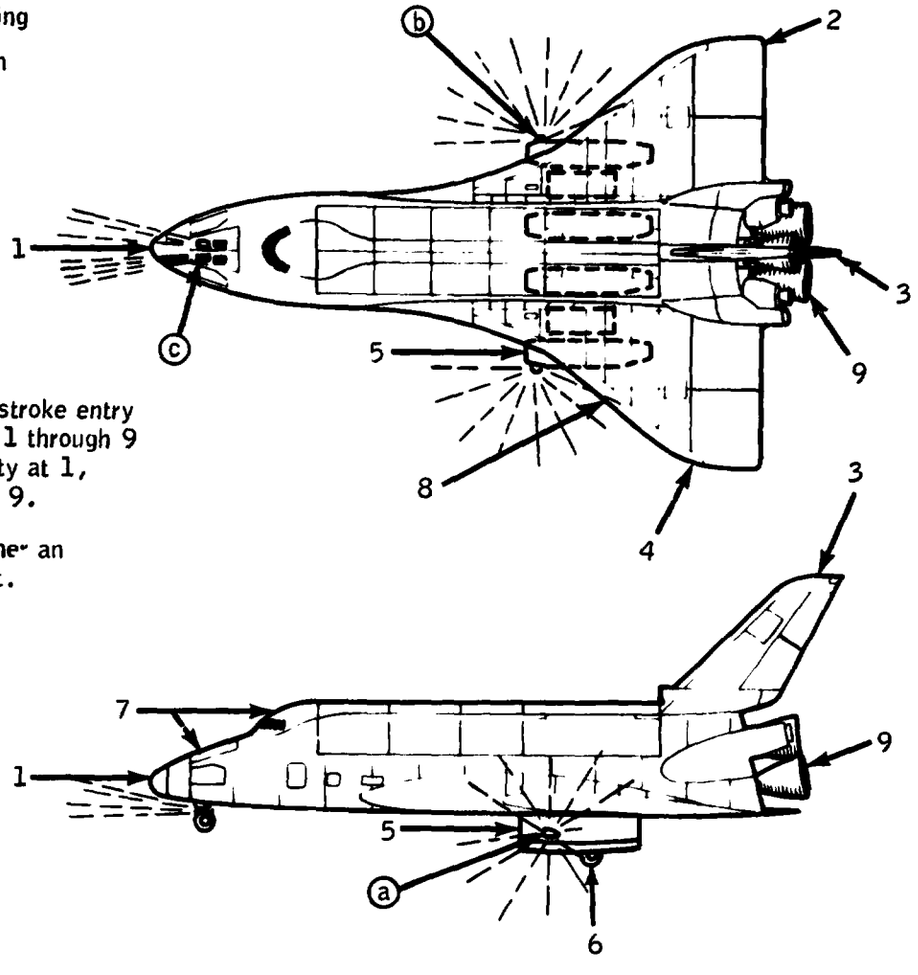
The most likely lightning entry/exit points of the Orbiter ferry phase are shown in figure 6-1.

External lighting

ⓐ Attitude running

ⓑ Anti-collision

ⓒ Landing



Notes:

1. Most likely lightning stroke entry and exit points are at 1 through 9 with highest probability at 1, followed by 2 through 9.
2. Each point can be either an entry or and exit point.

Figure 6-1.- Anticipated lightning stroke entry and exit points for orbiter ferry configuration.

7.0 VERIFICATION

A severe lightning current waveform model has been defined for the Space Shuttle as a design requirement and included in Appendix A of this document. The reproduction of this complete waveform would be expensive and difficult, therefore, some simplified test waveforms are prescribed for demonstrating compliance with the severe model requirements.

7.1 WAVEFORMS

The transient currents and voltages produced by simulation devices may be described by certain idealized waveforms. These same waveforms may be used as approximations to the actual lightning current, and to the currents and voltages produced by the lightning current.

The four most commonly encountered waveforms are shown on figure 7-1. The physically realizable waveforms (solid lines), and straight line approximations (dotted lines) are both shown. These waveforms describe both the amplitude and time history of the waveform. The most important factors that must be defined for each of the waveforms are:

7.1.1 Damped Oscillatory Waveform

a. Amplitude - A

b. Time to crest - t_1 (straight line approximation - t')

c. Period of oscillation - T [in terms of frequency, (f) T = 1/f]

d. Decrement or ratio of amplitudes of successive half cycles.

7.1.2 Exponential Waveform

a. Amplitude - A

b. Time to crest - t_1 (straight line approximation - t')

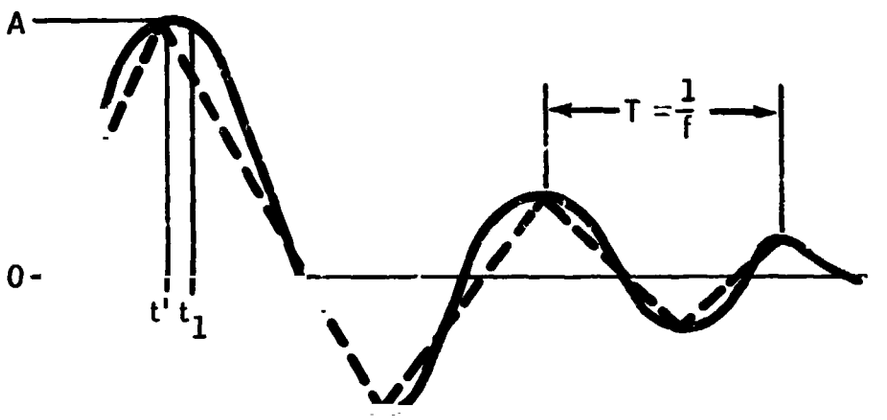
c. Time to half value - t_2

7.1.3 Exponential Waveform with Backswing

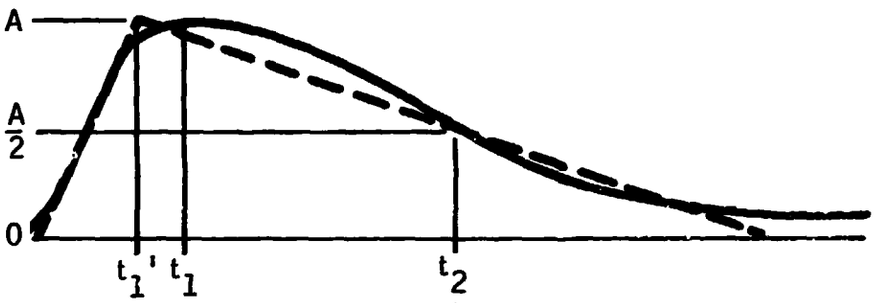
a. Amplitude - A (time to crest and time to half value same as the exponential wave).

b. Amplitude of the backswing - A2

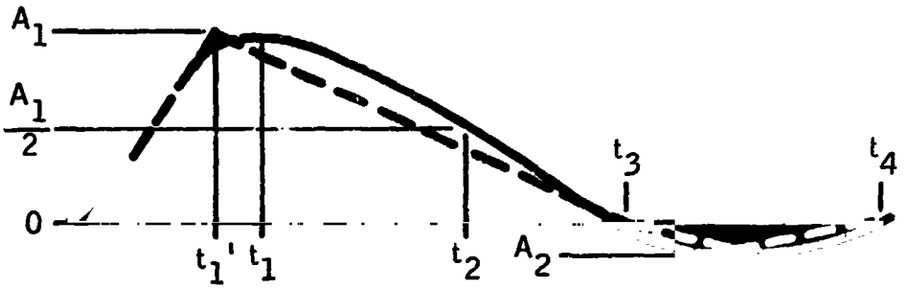
c. Duration of the backswing - t_4 minus t_3



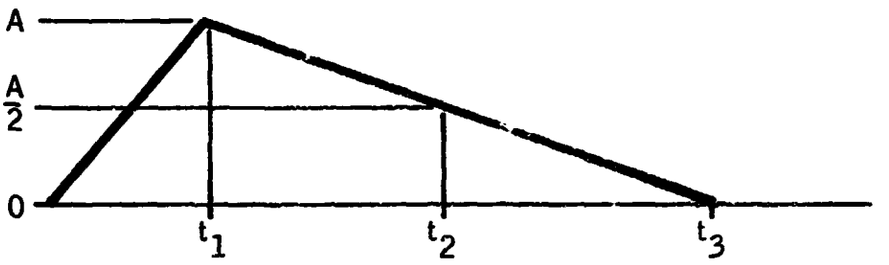
a) Damped oscillatory wave



b) Exponential wave



c) Exponential wave with backswing



d) Generalized triangular wave

Figure 7-1. - Description of waveforms.

7.1.4 Generalized Triangular Waveform

a. Amplitude - A

b. Time to crest - t_1

c. Time to half value - t_2

d. Duration - t_3

7.2 APPLICABILITY OF WAVEFORMS

7.2.1 Direct Effects

The solid lines of the damped oscillatory waveform and exponential waveform (fig. 7-1) should be used for exterior hardware and total vehicle tests. The solid lines in figure 7-1 indicate the general test waveforms which are defined in more detail in Appendix E. These waveforms are determined by the type of equipment available for artificial lightning generators, specifically capacitor banks firing into the test circuits, which results in damped oscillatory and exponential waveforms.

7.2.2 Indirect Effects Analysis

Analysis of indirect effects is most easily accomplished with a straight line approximation of the natural and artificial lightning current waveforms. These are illustrated by the dashed lines in figure 7-1, and are defined in more detail in Appendix E.

7.2.3 Indirect Effects Test

Test waveforms for indirect tests are determined both by the pulse sources and the coupling devices with resultant waveforms shown in b, c, and d portion of figure 7-1, and in more detail in Appendix E.

7.3 FLIGHT HARDWARE (ORBITER/SOLID ROCKET BOOSTERS/EXTERNAL TANK/ SPACE SHUTTLE MAIN ENGINES)

7.3.1 Component and Subsystem Level Tests - Direct Effects

7.3.1.1 A series of tests shall be made on those components of the structure most likely to be subjected to the direct burning, blasting, or mechanical effects of lightning. The purpose of these tests shall be to determine whether those components

will suffer unacceptable physical damage. Exterior hardware having a criticality of 1 shall be tested. Exterior hardware having a criticality of 2 and 3 should be tested, if analysis so indicates.

7.3.1.2 The items to be tested should include, but will not be limited to the following:

a. Navigation lights

b. Separation latching mechanisms

c. Guillotine devices

d. Fuel filler caps

e. Access doors

f. Umbilical systems

g. Umbilical covers

h. Antennas

i. Pitot tubes

j. Fuel vents

k. External structural skin joints

7.3.1.3 A more detailed discussion of the test waveforms to be used for direct effects testing is given in Appendix E.

7.3.2 Component and Subsystem Level Tests - Indirect Effects

7.3.2.1 A series of analysis and transient proof tests shall be conducted on a subsystem level.

7.3.2.2 The actual transient level to which lightning is expected to impress upon the equipment shall be calculated. Appendix F may be used as a guide to such calculations. On the ground, where the vehicle can be the entry point for lightning, actual transient levels impressed upon any associated ground hardware shall also be incuded in the calculations.

7.3.2.3 Each piece of electrical equipment shall be assigned a transient design level at which a transient proof test may be made to verify that the apparatus will not suffer adverse effects. The type of test (voltage or current), the type of application (common mode or line-to-line), the amplitude, and the frequency or wave-shape parameters shall be included in the complete specification of the transient test levels.

7.3.2.4 Transient proof tests are discussed in Appendix D. A series of transient levels shall be developed that are appropriate to the different types of apparatus and the electromagnetic environment to which that apparatus is exposed. Appendix D may be used as the initial guidelines for the development of such levels.

7.3.2.5 The actual transient level produced by lightning shall be verified to be less than the transient test level to which the equipment has been subjected or the transient design level, if the proof test has been waived.

7.3.2.6 The required margin between the actual transient level and the transient test or design level shall be determined from the guidelines given in Appendix D.

7.3.2.7 Transient proof tests shall be performed on all criticality 1 electrical equipment. Transient proof tests should be performed on criticality 2 and 3 electrical equipment, if analysis so indicates.

7.4 TOTAL VEHICLE TESTS

Simulated lightning tests shall be conducted on the Orbiter vehicle. The test vehicle should be outfitted with as complete a set of avionics equipment as possible, and be configured for the entry and ferry (altitudes below 50 000 feet) phases. The avionics equipment shall be operated during a representative portion of these tests to verify compliance with the requirements of this document. The generalized test waveforms to be used in the lightning simulation testing are shown in figure 7-1 and described in more detail in Appendix E. Waveforms more closely approximating those of Appendix A should be used, if available.

7.5 GROUND HARDWARE

7.5.1 Direct Effects

7.5.1.1 Vehicle-to-Facility Grounding

Verification of the 2.5-millichm requirement of paragraph 4.1.1 shall be made by analysis, and if practical, shall be verified periodically by actual measurement.

7.5.2 Indirect Effects

7.5.2.1 Equipment and Instrumentation Grounds.- Verification of the requirements of paragraph 4.2.1.1 shall be accomplished by measurement during initial facility construction and periodically, thereafter.

7.5.2.2 Continuity of Cable Shields.- The continuity of the overall cable shields, specified in paragraph 4.2.2.1, shall be verified prior to cable installation. Verification that overall shielding integrity is maintained after cable installation shall be performed, where practical.

7.5.2.3 Calculation of Actual Transient Levels.- Circuits of criticality level 1 and 2 shall be analyzed in accordance with Appendix D to determine the transient levels produced upon those circuits by lightning. This analysis shall be made in sufficient detail to determine both the differential-mode and the common-mode transients upon both the ground hardware and associated flight hardware.

7.5.2.4 Transient Design Levels.- Transient design levels shall be established for all ground hardware of criticality levels 1 and 2. These levels should be determined by analysis of design data, using the guidelines in Appendix D. The transient design levels shall include both common-mode and differential-mode interference. Transient design levels should be established for equipment of criticality level 3, if analysis so indicates.

7.5.2.5 Transient Proof Tests.- On ground hardware of criticality levels 1 and 2, transient proof tests or transient analyses shall be performed to demonstrate that the actual transient levels are lower than the assigned transient design levels by the margins given in Appendix D.

7.5.2.6 Transient Level Verification.- Provisions shall be made to measure the indirect effects of actual lightning on representative circuits when ground hardware is connected to the vehicle during rollout and on the launch pad. These measurements are to be used for evaluating the equipment actual transient levels previously calculated in accordance with paragraph 7.5.2.3.

8.0 WEATHER RESTRICTIONS

To be determined.

GLOSSARY OF TERMS

Adverse effects	Adverse effects are defined as those conditions that damage equipment required for safe operation of the vehicle; causes malfunction or inadvertent operation of equipment or systems required for continued safe operation of the vehicle; requires immediate action by the crew to assess and/or correct for damage or malfunction during time critical flight phases (i.e., launch, ascent, atmospheric recovery, approach, and landing through rollout); and causes electromagnetic coupling which annunciates fault status requiring crew assessment.
Arc attachment point	The point or points at which a lightning channel attaches to a metallic surface.
Air terminal	The combination of elevation rod with tip or point if used, and brace, or footing placed on upper portions of structure to intercept lightning strokes.
Attenuation	Reduction in magnitude of an electric or magnetic field, a current, or a voltage expressed in decibels, where $\text{attenuation (dB)} = 20 \log_{10} \frac{Q_1}{Q_2}$ Q = current or voltage
Bearing assembly	A group of individual bearings which support a single movable structure.
Cable	Any quantity of electrical wires grouped together to form a single bundle.
Cable ladder or cable tray	Refers to standard supporting members for signal and power cable groups.
Cable shield	Any metallic covering on a single (coaxial) or multiple conductor cable. The shield can take the form of tinned or untinned copper braid, wrapped foil tape, or a lead jacket.

Cone of protection This term refers to the volume of a cone in which objects are very unlikely to be struck directly by lightning. The cone of protection of a grounded air terminal or mast of conducting material is the space enclosed by a cone, which has its apex at the highest point of the air terminal or mast and a radius at the base which is a function of the mast height. A 1:1 cone has a base radius equal to its height, and a 2:1 cone has a base radius equal to twice its height.

Criticality category Criticality categories are defined as follows:

Category	Definition
1	Loss of life or vehicle
2	Loss of mission
3	All other

Flash The total series of electrical and luminous effects comprising a single lightning phenomenon. Typically, the duration of a flash is several tenths of a second.

Margin The required ratio, expressed in dB, between the transient design level and the actual transient level which lightning is expected to produce on the interconnecting wiring.

May For this document, may is used in the permissive sense.

Return stroke Any one of the high current, brightly luminous, upward-moving surges, that occur during a cloud-to-ground flash. Upward moving return strokes are preceded by a downward moving leader streamer from cloud-to-ground.

Shall For this document, shall is used in the mandatory sense.

Should For this document, should is used in the recommended sense.

Stroke Any one of the major electrical and luminous effects, the entire series of which make up the lightning flash. Typically, stroke duration is much less than a millisecond. Many authors restrict the term "stroke" to the "return stroke" of the cloud-to-ground flash.

Terminal equipment	Any type of electrical equipment interfacing with an electrical conductor - any electrical conductor thus interfaces with two pieces of terminal equipment, one at each end.
Transient design level	A level at which a transient proof test is made. The transient design level specification includes the amplitude at which the test is made and the frequency of an oscillatory transient, or the time to the crest as well as the decay of an exponential wave.
Transient proof test	A test in which current or voltage transients are injected into terminals of electrical equipment to prove that adverse effects are not encountered.

APPENDIX A

LIGHTNING MODELS

The currents flowing in a lightning flash to ground are conveniently separated into three categories:

a. Return stroke surges	Peak current on the order of up to 100 000 A or more.
	Duration on the order of tens of microseconds.
b. Intermediate currents	Peak current on the order of up to 10 000 A or more.
	Duration on the order of milliseconds.
c. Continuing currents	Peak current on the order of up to 1000 A.
	Duration on the order of hundreds of milliseconds.

Currents of types b and c are principally responsible for damage such as hole-burning while type a currents mainly produce explosive effects and undesirable coupling transients.

In general, the time structure of lightning currents is less variable between individual flashes than are the amplitudes. It follows that severe lightning models are best developed first in terms of amplitudes, with subsequent secondary adjustments to the time structure in order to obtain overall physical reality. Furthermore, there is little connection within an individual discharge between the severity of the three categories of current; in other words, even if an initial return-stroke surge is severe, this has minimal influence on the severity of a following continuing current.

The current-time history for a model lightning flash to ground is shown diagrammatically in figure A-1 with some further details being presented in table A-I. The flash is a very severe discharge. The model is formulated in terms of certain key points (A through I in figure A-1) at which specific values of current, i, and time, t, are attained. Between successive key points the current is assumed to change in a steady straightline fashion with time.*

*This simple representation leads to discontinuities in the rate of change of current (di/dt). However, when necessary — as in some computing work — these discontinuities are easily accomodated by various mathematical devices.

The model consists of six current stages: a first return stroke including both a main-current surge and an intermediate current; a continuing current in two phases; and a second subsequent stroke again comprising a main surge succeeded by an intermediate current. The continuing current is modeled in two phases because material damage produced by continuing currents depends on actual time and current values (Appendix B), and is not — as is often incorrectly believed — a function of charge transfer alone. It is possible that special types of damage could be produced by a subsequent stroke following a continuing current; hence the addition of the second stroke.

The model represents a very severe flash. For instance, the first stroke involves a peak current of 200 kA and a rate of current rise of 100 kA/μs; these values are exceeded, respectively, in some 0.7 percent and 2 percent of the first strokes. Also, the charge transfer represented by the continuing currents is 155 coulombs with an average current of 700 A in the initial phase; these magnitudes are surpassed, respectively, in 0.5 percent and 1 percent of continuing currents. Again, a peak current of 100 kA is only exceeded in 0.7 percent of subsequent strokes. A further important point is that the values of many lightning parameters are not interconnected. Thus, in our model flash, we have a first stroke peak current of 200 kA, a total charge transfer of 200 coulombs, and a subsequent stroke peak current of 100 kA; since these three parameters are essentially unrelated, it follows that the three specified values are all exceeded in the same discharge for less than one in one-hundred thousand flashes to ground.

The model is essentially developed for applied purposes and it has consequently been simplified appropriately in both the analytical and physical respects. In physical reality, a severe discharge would have far more strokes and also, more phases of continuing current than indicated on figure A-1; however, the integrated effects of a very severe natural discharge and of the model are similar.

Intracloud discharges are less severe than flashes to ground largely because of the absence of the large sudden return-stroke surges. Thus, if material and equipment are unaffected by the severe ground-discharge model, material and equipment will also be immune to intracloud flashes.

Further information on the concepts advanced in this Appendix is summarized in two sources:

1. Lightning (McGraw-Hill) by M. A. Uman (1969).

2. "A Ground-Lightning Environment for Engineering Usage" by N. Cianos and E. T. Pierce, Stanford Research Institute report (1972).

TABLE A-I.- DETAILS OF LIGHTNING MODEL

Stage	Key points		Rate of current change	Charge passing
1. First return stroke surge	t = 0	i = 0	Linear rise - 100 kA/μs	0.2 C
	t = 2 μs	i = 200 kA	Linear fall - 193 kA in 98 μs	∿ 10.2 C
	t = 100 μs	i = 7 kA		
2. First stroke intermediate current	t = 100 μs	i = 7 kA	Linear fall - 6 kA in 4.9 ms	19.6 C
	t = 5 ms	i = 1 kA		
3. Continuing current - first phase	t = 5 ms	i = 1 kA	Linear fall - 600 A in 50 ms	35.0 C
	t = 55 ms	i = 400 A		
4. Continuing current - second phase	t = 55 ms	i = 400 A	Steady current	120.0 C
	t = 355 ms	i = 400 A		
5. Second return stroke surge	t = 355 ms	i = 400 A		
	t = 355.002 ms	i = 100 kA	Linear rise ∿ 50 kA/μs	∿ 0.1 C
	t = 355.1 ms	i = 3.5 kA	Linear fall - 96.5 kA in 98 μs	∿ 5.0 C
6. Second stroke intermediate current	t = 355.1 ms	i = 3.5 kA		
	t = 360 ms	i = 500 A	Linear fall - 3 kA in 4.9 ms	9.8 C

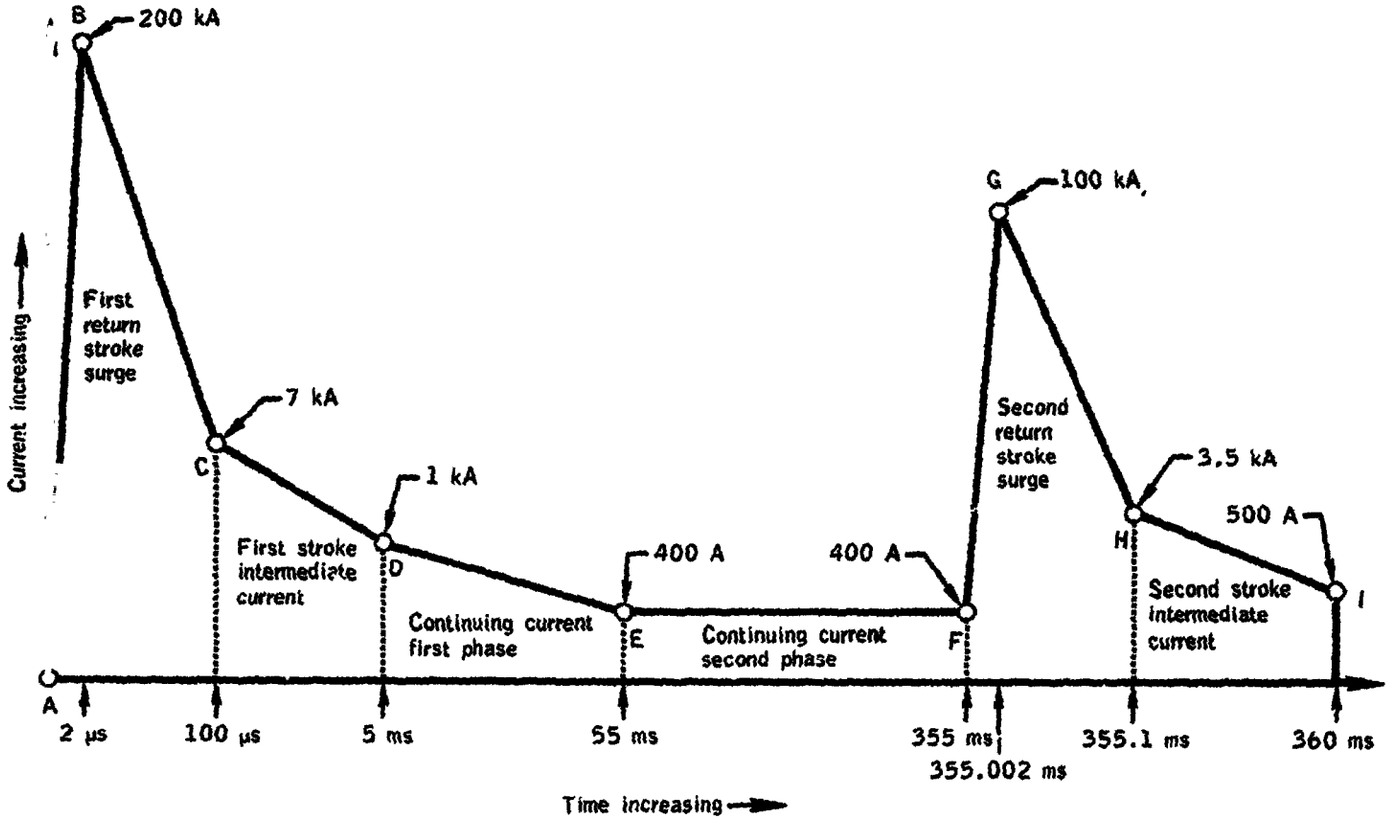


Figure A-1.- Diagrammatic epresentation of lightning model.
(Note that the diagram is not to scale.)

APPENDIX B

HEATING AND PUNCTURE OF METALLIC SURFACES BY LIGHTNING

At and near the point (circular spot on the order of 0.5 inch or less in diameter) that lightning enters or leaves a metallic surface, energy is transferred to that metal. The result is heated metal and possible puncture (burn or melt-through) of the metal. In general, the thicker the metal and the higher its electrical and thermal conductivities, the less severe the damage. Most heating effects are due to lightning currents in the one-hundred to several-thousand ampere range with durations of hundreds of milliseconds to a few milliseconds. (The intermediate and continuing current phases of the lightning model.)

Analytical approaches to this heat transfer problem are complicated by the lack of knowledge on the fraction of the energy input delivered to evaporation and sputtering, which may be large, and the lack of knowledge on the thermal and electrical properties of metals at high temperatures. The best available information on lightning-metal interactions has been obtained by laboratory simulation. The results of these studies are probably indicative of more damage than would be produced by actual lightning, since the laboratory-arc contact spot is generally not as free to move on the surface as is the actual lightning.

Experimental data due to Brick are shown in Figures B-1 and B-2. Figure B-1 indicates the charge transfer, the time for that transfer, and the steady current needed for that charge transfer in order to produce a burn-through of aluminum sheets (back surface to 660° C) of various thicknesses. Figure B-2 gives charge, time, and current to raise the back surface of titanium to 1320° C (jet-fuel ignition temperature). The melting point of titanium is about 1700°C.

Experience with commercial aircraft and laboratory studies have shown that windstream and electromagnetic effects operate to move the point-of-arc attachment. This motion is greater for some materials than for others depending largely on surface properties. Electrode configurations may tend to render the arc stationary. Usually, however, the windstream movement effects are dominant - except on trailing edges - so that "sticking" times on conducting material normally used on aircraft are of the order of a millisecond. For bare skins, the intermediate current phases are the most critical in that they cause damage with minimum charge transfer. Even with sweeping effects, the intermediate current can puncture thin skins at low air velocities.

Further information can be obtained from the following sources:

1. R. O. Brick, "A Method for Establishing Lightning Resistance/Skin Thickness Requirements for Aircraft", USAF Avionics Laboratories, Wright-Patterson AFB, Ohio, Proceedings, 1968 Lightning and Static Electricity Conference, December, 1968, Miami, Florida.

2. R. O. Brick, L. L. Oh, S. D. Schneider, "The Effects of Lightning Attachment Phenomena on Aircraft Design", USAF, Proceedings, 1970 Lightning and Static Electricity Conference, December, 1970, San Diego, California.

3. R. H. Evans and J. Phillpott, "Lightning Simulation and Testing in Relation to Specification MIL-B-5087", Proceedings, 1972 Lightning and Static Electricity Conference, December 12, 1972, Las Vegas, Nevada.

4. M. M. Newman, J. R. Stahmann, J. D. Robb, and T. Ghen, "Lightning Discharge Sweeping Effects on Current Pitting of Aircraft Skins", L&T Report No. 530, April, 1971; Lightning & Transients Research Institute, St. Paul, Minnesota.

5. M. J. Kofoid, "Lightning Discharge Heating of Titanium Aircraft Skins", Boeing Scientific Research Laboratories; Document D1-82-0752, September, 1968.

6. K. B. McEachron and J. H. Hayenguth, "Effect of Lightning on Thin Metal Surfaces", Transactions AIEE 61, pages 559-564 (1942).

7. P. L. Bellaschi, "Lightning Strokes in Field and Laboratory III", Transactions AIEE 60, pages 1248-1256 (1941).

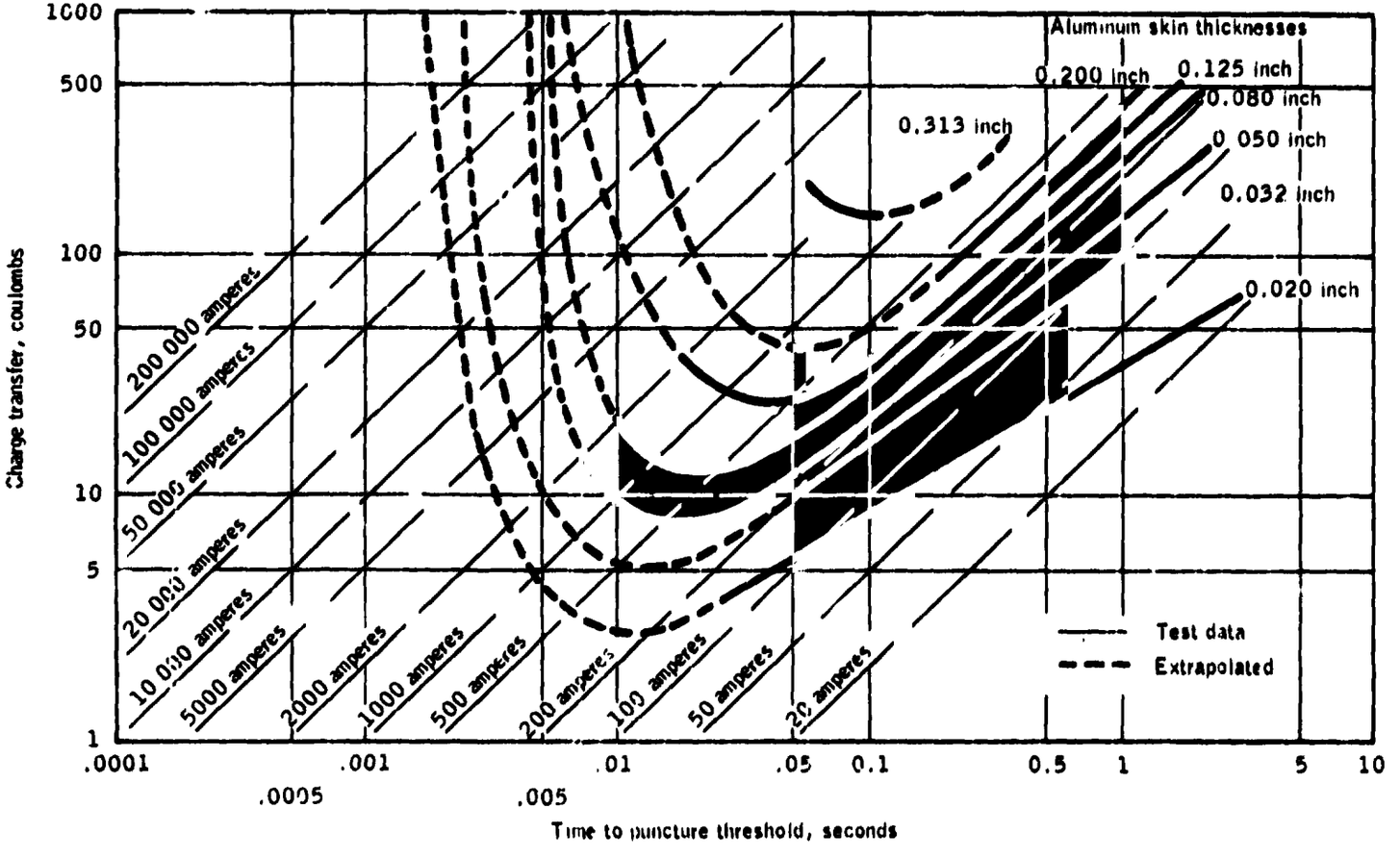


Figure B-1.- Aluminum skin puncture threshold

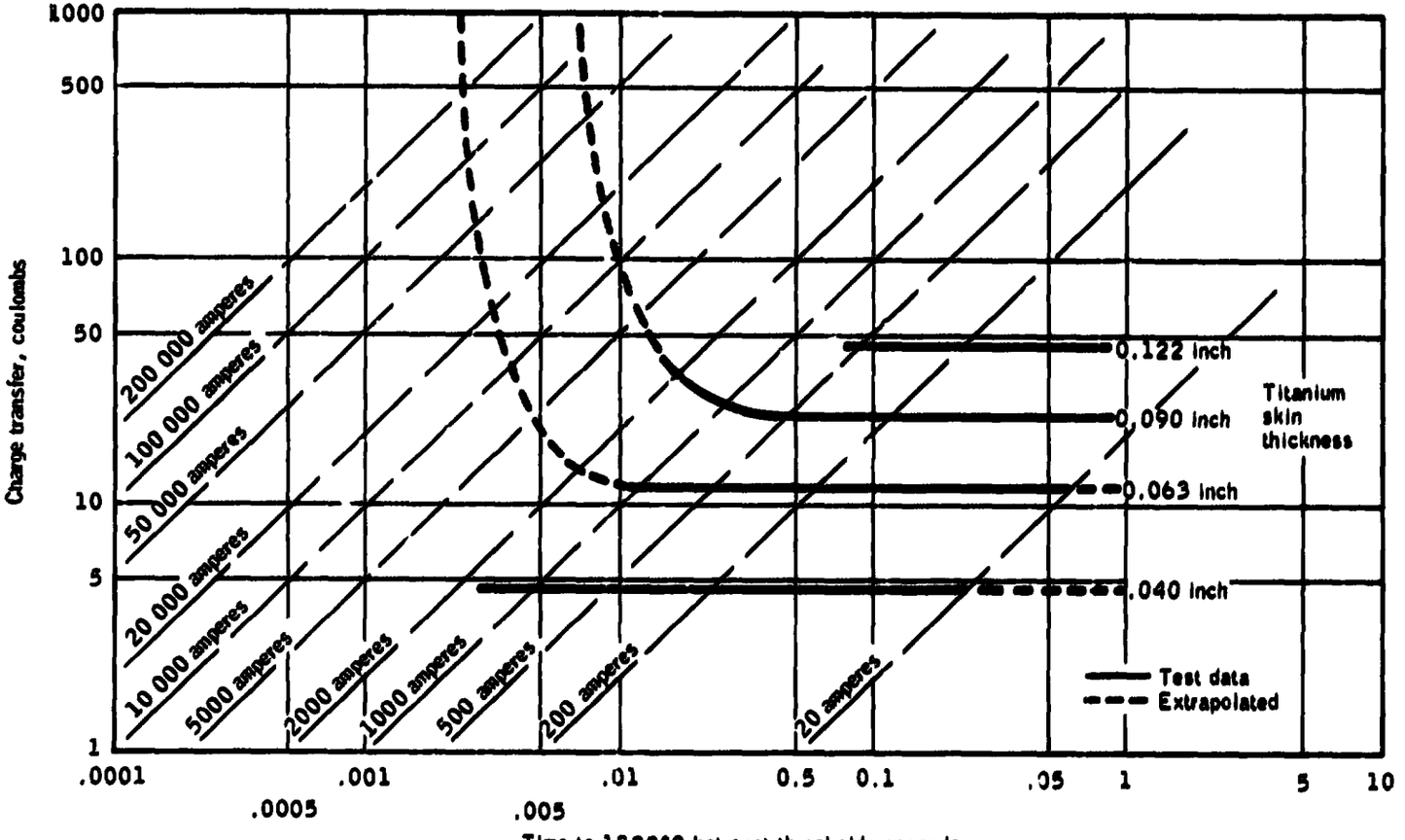


Figure 8-2.- Titanium hot spot threshold

APPENDIX C

TRANSIENT PROTECTIVE DEVICES

Transient protective devices offer the possibility of improving the ability of a system to withstand the electromagnetic effects of lightning.

There are two basic types of overvoltage or transient protection devices, those which on sensing an overvoltage switch to a low impedance state and thus cause the impressed voltage across them to collapse to a low value, and those which on sensing an overvoltage tend, by virtue of their non-linear voltage-current relation, to maintain the voltage at that level, but do not collapse the voltage. Examples of the first type are spark gaps and arcing dielectrics. Examples of the second type are Zener diodes and varistors. There are also devices, which on sensing an overvoltage, interrupt the power flow to the load. If this interruption is accomplished by electromechanical means, they should not be considered transient protection devices because they are inherently slow to respond.

Switching devices inherently offer greater surge power handling capability than do the Zener or varistor types of devices. The instantaneous power dissipated in a transient protective device is the product of the surge current flowing through the device and the voltage across the device. For a constant surge current, a switching device, like a spark gap across which the voltage is low while in the conducting state, will have less power released in it than a device like a Zener diode across which the surge voltage remains high. For a given surge power handling capability, a spark gap will thus be smaller physically than a Zener diode or varistor device.

Another fundamental difference between switching devices (spark gaps) and non-switching devices (Zener diodes or varistors) relates to their recovery characteristics after the surge has passed. If a line is protected by a spark gap and if that line is connected to a source of energy (a power bus, for example), that energy source must be disconnected from the line before the spark gap can switch back from its low impedance conducting state to its high impedance non-conducting state. Generally, this requires opening a circuit breaker on the line. A Zener diode or varistor effectively ceases to conduct as soon as the voltage returns to its normal value. Operation of remote circuit breakers is not required. Transient protective devices are not a panacea. However, all types of overvoltage protection devices inherently operate by reflecting a portion of the surge energy to its source and by diverting the rest into another path, all with the intention of dissipating the surge energy in the resistance of the ground and in the interconnecting loads. The alternative

to reflecting the energy is to absorb the surge energy in an unprotected load. Reflection and diversion of the surge energy are not without their hazards.

a. The reflected energy can possibly appear on other unprotected circuits.

b. Multiple reflections may cause the transient to last longer than it would otherwise.

c. The spectral density of the energy may be changed, with either high or low frequencies being enhanced. Interference problems on other circuits may well be enhanced even though the risk of damage to the protected circuit is reduced.

Most commonly, the type of transient protective device to be used depends on the amount of surge energy to be reflected. Generally, this energy decreases the further away one gets from the stroke. The surge energy to be expected can also be related crudely to the normal operating power of the circuit involved. One would normally expect lower surge levels on low-voltage signal circuits than on medium power control circuits and even less than on main power distribution busses. One might thus logically use Zener diodes on individual circuit boards, varistors on terminal boards, and spark gaps on leads running to prime entry and exit points.

A summary of the advantages and disadvantages of the various transient protective devices is given in table C-1.

Further information can be obtained from the following sources:

1. E. G. Arrowsmith, "Lightning Discharges and Your Equipment," The Electronic Engineer, October 1966.

2. R. E. Buies, F. A. Fisher, "Techniques and Devices for the Protection of Electrical and Electronic Circuits from Lightning Transients," General Electric Company, Contract No. AF29(601)-5402, June 1963.

3. G. E. Morgan, V. A. Bascou, W. H. Cordova et al., "Final Report on the Evaluation of Surge Protective Devices for EMP Hardening Applications," Autonetics, North American Rockwell, C72-712/201, Contract No. F29601-72-C-0028, December 1972.

TABLE C-1.- COMPARISONS AMONG VARIOUS TYPES OF TRANSIENT PROTECTIVE DEVICES

Device type	Advantages	Disadvantages	Remarks
Spark gap	Simple and reliable. Easily fabricated. Very low voltage drop during conducting state. Bilateral operation - same characteristics on either polarity.	Relatively high spark overvoltage. Arc must be extinguished by removing voltage. Seldom available in conveniently packaged assemblies; must be designed for each specific use.	Generally consists of two metal electrodes separated by air with a minimum spark over voltage of 1500 to 3000 V.
Gas diode	Low cost. Small size. Low spark overvoltage (usually 60 to 100 V). Can pass high current for short times. Self-healing.	Poor volt/time characteristics. Will continue to conduct if driving voltage is above 60 to 100 V.	Neon bulb is typical example.
Zener diodes	Small size. Easily mounted. Low firing voltage. Low dynamic impedance when conducting. Self-extinguishing when applied voltage drops below Zener level, conduction ceases.	Expensive. Not bilateral. Voltage across diode does not switch to low value when conducting, but remains at Zener voltage. Not available for voltages below about 5 V. Normally not available for voltages above a few hundred volts.	Can be used to clip a surge voltage and limit the surge to the Zener voltage. Well adapted to semiconductor protection.
Forward-conducting diodes	Small size. Low cost. Provides protection at very low voltage levels. Good surge-current ratings.	Not bilateral. Conduction may occur at normal signal levels with possibility of clipping and frequency multiplication effects. Relatively high capacitance.	Includes standard germanium and silicon diodes.
Silicon-controlled rectifiers	Excellent surge-current rating. Low voltage drop when conducting. Suitable for low voltage circuits.	Must be triggered by an auxiliary circuit. Does not reset automatically. Not bilateral. Expensive.	Can be used as a one-polarity spark gap to prevent surges.
Varistors	Low cost. Small size. Pass higher current than Zener diodes. Self extinguishing. May be bilateral devices. Operate at either polarity.	May have high capacitance. Cannot be clamped at lower voltages. Not available with ratings as low as Zener diodes.	More adaptable to terminal boards, distribution panels, and printed circuits. Zinc oxide types have best overall performance.

APPENDIX D

TRANSIENT LEVELS

Verification of the ability of equipment to withstand the indirect effects of lightning will be provided through the assignment of a series of transient design levels and the implementation of a series of transient proof tests conducted at transient test levels which will generally be, but need not be, identical to the transient design levels.

The transient proof test is a test wherein currents, voltages, or both, are injected into the interface terminals of avionics equipment. The levels at which the proof test is conducted and the transient levels to which the equipment is designed must be appropriate for both the type of equipment under test and the electromagnetic environment to which the equipment and wiring is exposed.

Compliance with the terms of this document will be assumed, if the actual transients on interfacing cables are shown by analysis or test to be lower, by a specified margin, than the transient test level at which the transient proof test was made or the transient level to which the equipment was designed.

Transient Design Levels

Transient design levels will be different for different types of equipment, and will be based on levels at which avionics equipment can be reasonable expected to survive. It would, for example, be unrealistic to place the same transient design level on a solenoid-operated actuator and a digital control unit. To do so would probably require either unnecessary shielding of the wiring to the actuator, or require unnecessarily complex protective circuits in the control unit.

Determining a realistic level for different types of equipment may involve test programs to determine actual susceptibility levels. If such susceptibility levels have been determined, a transient design level of a lower amplitude should be specified. An estimate should be made of the difference between the actual susceptibility level and the assigned transient design level, since this difference will be one of the factors determining the ultimate margin required during the verification program.

If no measured susceptibility levels are known, it may be possible to estimate a susceptibility level and from that determine an appropriate transient design level. In such a case, the difference between the estimated susceptibility level and the assigned transient design level should

be greater than if the selection were based on measured susceptibility levels. In other cases, no information on susceptibility levels may be available, and thus, it will be necessary to arbitrarily assign a transient design level.

Transient Test Waveforms

The most commonly used type of transient test waveforms will be of a damped oscillatory nature, as is shown in the a portion of figure 7-1. An alternative waveform is an overdamped or exponential transient, as is shown in the b portion of figure 7-1. If an exponential transient is coupled into the circuit under test by transformer coupling, there will inevitably be a backswing. The amplitude and duration of this backswing may be left uncontrolled provided that the amplitude of the backswing is less than 25 percent of the amplitude of the main pulse.

Margins

In each case, a margin shall be specified between the transient design level and the actual transient level permitted by the cable system. The definition of margin shall be:

$$\text{Margin} = (\text{decibel or dB}) = 20 \log_{10} \frac{\text{Transient design level}}{\text{Actual transient level}}$$

The required margin will be a function of the criticality of the particular circuit and the degree of uncertainty in the analyses of actual transient levels and transient design levels. The required margin will be greater:

a. For the more critical circuits.

b. For that equipment in which the actual performance of a transient proof test is waived.

c. For those circuits in which the calculation of actual transient levels is the least precise.

The required margins may be calculated by the formula:

Margin (expressed in dB = X + Y + Z . . . . . 1)

Where X = A factor depending on the criticality of the circuit

Y = A factor relating to the extent to which actual susceptibility is known in terms of the assigned transient design level.

Z = A factor relating to the degree to which the actual transient level is known.

X or Criticality Factor

Criticality level 1	X = 6 dB
Criticality level 2	X = 3 dB
Criticality level 3	X = 0 dB

Y or Susceptibility Factor

Difference between assigned transient design level and susceptibility level known by actual test	Y = 6 dB minus actual value expressed in dB
Difference between assigned transient design level and susceptibility level estimated by analysis	Y = 6 dB minus one-half estimated value expressed in dB
Transient design level assigned arbitrarily - actual susceptibility level unknown	Y = 6 dB
Difference known from susceptibility testing, but transient proof test waived	Y = 9 dB minus actual value expressed in dB
Difference estimated, but transient proof test waived	Y = 9 dB minus one-half estimated value expressed in dB
Transient design level assigned arbitrarily, actual susceptibility level unknown, transient proof test waived	Y = 9 dB

Z or Transient Level Factor

Transient levels estimated only from data given in Appendix F	Z = 6 dB
Transient levels estimated from detailed analysis, analysis not reviewed by Lightning Protection Committee	Z = 3 dB

Transient levels estimated from detailed analysis, analysis reviewed and approved by Lightning Protection Committee	Z = 0 dB
Transient levels known from low level injected current tests with results scaled to full lightning current level	Z = -3 dB
Transient levels known from full scale injected current tests	Z = -6 dB

Transient design levels may be assigned in terms of either open-circuit voltages or short-circuit current, as delivered from sources having realistic voltage, energy, and internal impedance levels. In some cases, either a voltage or current test may be inappropriate. A test specification that calls for an injected current of 10 amperes to be applied to a circuit terminated in a high impedance (open relay contact, inductive solenoid coil, or emitter-follower circuit) would clearly be inappropriate. Generally, a current test will be most appropriate for electronic circuits, and a voltage test most appropriate for inductive apparatus, transformers, motors, solenoids, etc. If the apparatus is protected by a surge protective device, a combined voltage and current test is appropriate; a voltage test to demonstrate the voltage-limiting characteristics and a current test to demonstrate the ability to handle the surge energy.

Actual Transient Levels

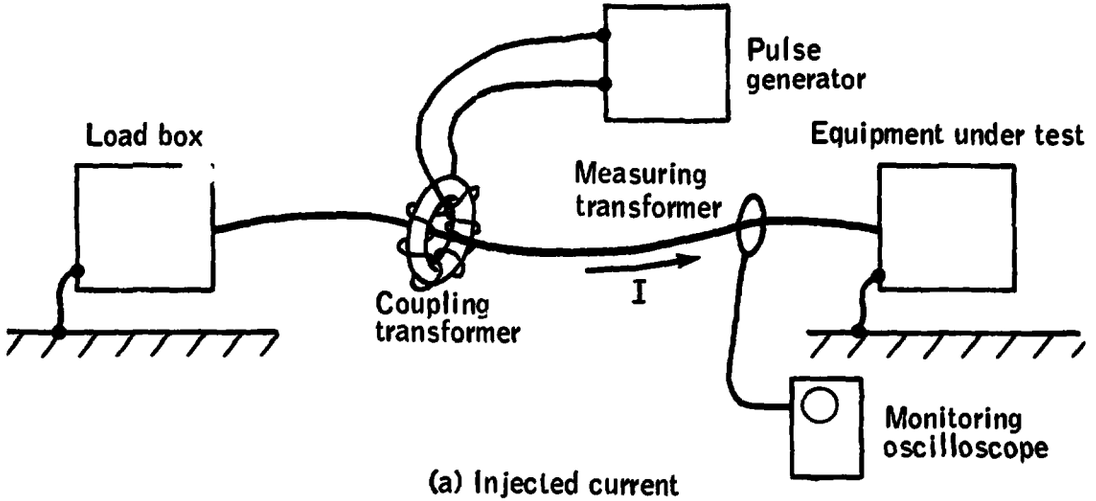
The calculation of actual transient levels that will appear on cable systems is a task of sufficient complexity as to be beyond the scope of this document. One approach to determination of these actual transients is given in Appendix F.

Methods of Conducting Tests

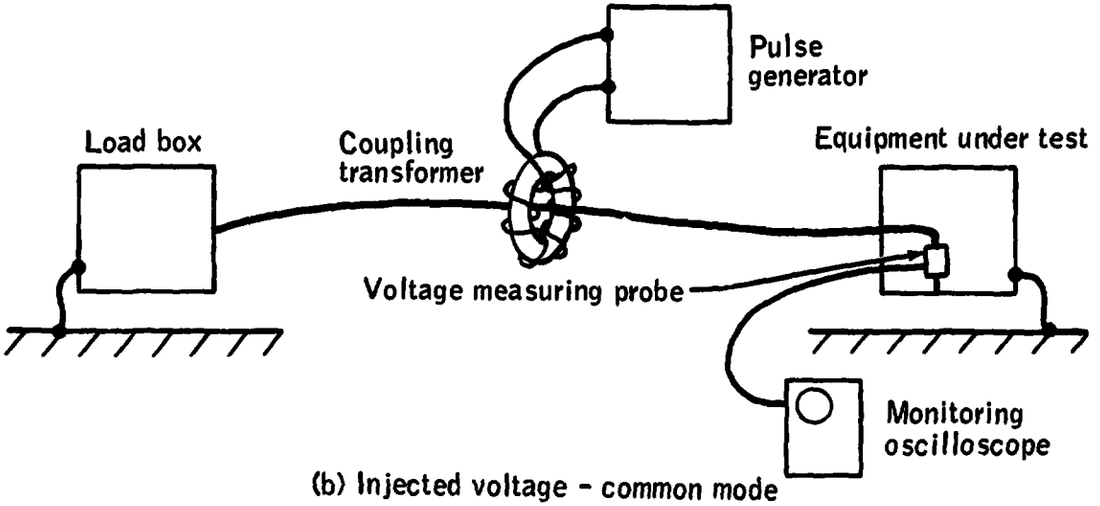
Fundamental to the conduct of a transient proof test must be the understanding that the transient generators used to inject transients into terminals of apparatus must inject reasonable amounts of power into those terminals. This implies that generators must employ voltage and stored-energy levels and have internal impedances appropriate to the voltage, current, and energy levels that lightning will produce on the cable systems.

Most commonly, the transient proof test will be performed on a common mode or line-to-ground basis and on a complete cable harness. In such a case, the transient proof test may be made using a transformer-coupling technique as shown on figure D-1.

In some cases, it will be desirable to inject voltages on a line-to-line basis. This may be done using the technique shown on figure D-2. Transient proof tests may also be performed by directly inserting current into the cable shields. Detailed development of test techniques is beyond the scope of this document. Sample work sheets for the assignment of transient levels and margins are shown in figures D-3 and D-4.



(a) Injected current



(b) Injected voltage - common mode

Figure D-1.- Transformer injection of transients.

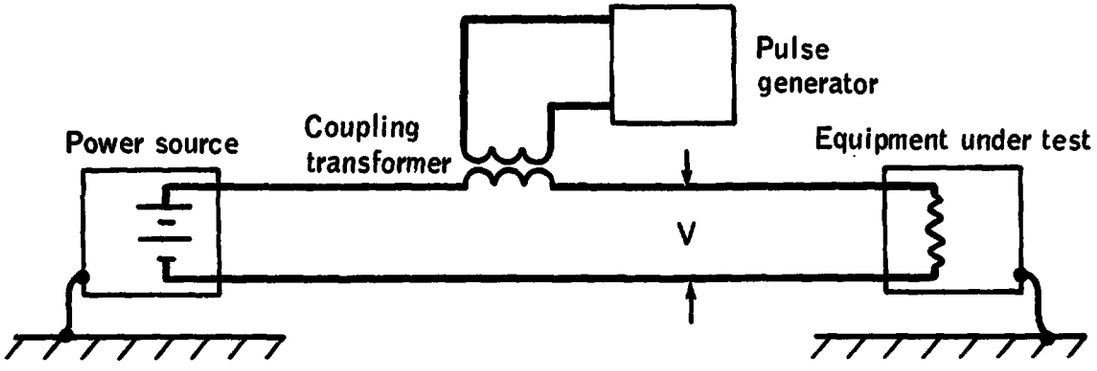


Figure D-2.- Transformer injected transient voltage - line to line.

Type of equipment	Test type	Test level	f	T_1	T_2	Required margin				Actual transient level	Remarks
						X	Y	Z	Sum		
28V computer power bus	V,L-L exp	56V	NA	2us	100MS	6	6	6	18		
Solenoid actuator	V,CM osc	200V	1MHz	NA	NA	0	9	-3	6		
Computer to IOB	I,CM osc	1A	1MHz	NA	NA	6	6	0	12		
				Samples							

Figure D-3.- Sample summary sheet of transient levels and verification.

TYPE EQUIPMENT

TYPE OF TERMINALS UNDER TEST

EQUIPMENT MOST SUSCEPTABLE TO:

TYPE OF TEST TO BE MADE (Check as appropriate)

Voltage ☐ Common mode ☐ Oscillatory ☐

Current ☐ Line-to-line ☐ Exponential ☐

f = _____

T_1 = _____ Assigned level _____

T_2 = _____ Design ☐
Test ☐

CALCULATION OF REQUIRED MARGINS (Check as appropriate)

Criticality 1(X = 6dB) ☐ 2(X = 3dB) ☐ 3(X = 0dB) ☐

Susceptability factor (Y)
- Known by test (Y = 6dB minus actual value) ☐
- Known by analysis (Y = 6dB minus one-half estimated value) ☐
- Unknown (Y = 6dB) ☐
- Transient proof test waived
  - NO (0dB) ☐
  - YES (Add 3dB to value of Y) ☐

Actual transient level factor (Z)
- Estimated from appendix F (Z = 6dB) ☐
- Known by analysis (Z = 3dB) ☐
- Known by analysis plus review (Z = 0dB) ☐
- Low level surge test (Z = -3dB) ☐
- High level surge test (Z = 6dB) ☐

Require margin X + Y + Z = _____

Figure D-4.- Sample work sheet for transient level assignments.

APPENDIX E

TEST WAVEFORMS DESCRIPTIONS

A severe lightning current waveform model has been defined for the Space Shuttle as a design requirement and included in Appendix A of this document. The reproduction of this complete waveform would be expensive and difficult and therefore, some simplified test waveforms are prescribed for demonstrating compliance with the severe model requirements. These waveforms are based primarily on standard practice at aircraft lightning laboratories. The waveforms have tolerances that are intentionally broad so that more than just a few laboratories can produce them. They do represent moderate to severe lightning effects.

For test purposes, a natural lightning discharge may be arbitrarily divided into high-, intermediate-, and low-current components, and high current rate-of-rise, all of which have different damage effects. Each part of an aerospace vehicle may be vulnerable to one or more specific lightning current components. High-voltage waveforms are used to check dielectric puncture and attachment points.

The voltage and current test waveforms are generated by using capacitor banks in various series and parallel combinations. Most of the effects of lightning are reproduced by these waveforms.

The test waveforms, illustrated in figure 7-1, are in general terms. Specific waveforms applicable to the various phases of the test program include:

Full Scale Testing

Total vehicle test phases (primarily for assessment of indirect effects).

a. Fast wave - A damped oscillatory waveform (fig. 7-1) at a frequency, f, of 100 (±50 percent) kilohertz with an amplitude, A, of 10 (±10 percent) kiloamperes. This component, particularly with its front of wave firing transients, simulates the higher frequency components in the lightning discharge high current return stroke.

b. Slow wave - A damped oscillatory waveform (fig. 7-1) at a frequency, f, of 2 (±50 percent) kilohertz with an amplitude, A, of 20 (±10 percent) kiloamperes. This component simulates the lower frequency components in the lightning discharge.

c. Unidirectional wave - A generally exponential waveform (fig. 7-1) that most closely simulates a natural lightning stroke waveform, with a virtual front time, t_1, of 2 (±50 percent) microseconds and a time to 50 percent of crest on the tail, t_2, of 50 (±50 percent) microseconds, with an amplitude, A, of 100 amperes or greater. Induced voltages resulting from this waveform must be extrapolated to full threat levels.

Component Testing

a. High current rate-of-rise (for assessment of indirect effects) - A damped oscillatory waveform (fig. 7-1) at a frequency, f, of 250 (±20 percent) kilohertz with an average rate-of-rise during the first quarter cycle of 100 000 (±50 percent) amperes per microsecond.

b. High current (for such direct effects as sparking, magnetic force, shock wave, and for assessment of indirect effects) - A damped oscillatory waveform (fig. 7-1) with a frequency, f, of 10 (±50 percent) kilohertz, and an amplitude, A, of 200 000 (±10 percent) amperes, except when stroke sweeping effects preclude the probability of more than one stroke entering at one place, in which case, the current beyond the first half cycle may be deleted.

c. Intermediate current (for such direct effects as slow pressure buildup and metal skin puncture) - An exponential waveform (fig. 7-1) with an amplitude, A, of 5000 (±10 percent) amperes and 1 by 3 (±30 percent) millisecond waveform (t_1 = 1 millisecond and t_2 = 3 milliseconds).

d. Long-duration continuing currents (for direct skin puncture effects) - A rectangular waveform (not illustrated) at 400 (±10 percent) amperes dc with a duration of 0.4 (±10 percent) second.

e. A high-voltage waveform (for such direct effects as dielectric puncture and arc attachment studies) applied at a rate-of-rise of 1000 kV per microsecond (±50 percent) across an air gap set so that flashover to the test piece occurs on the wavefront. This waveform would be similar to that shown in the b portion of figure 7-1, but probably limited by dielectric breakdown prior to time t_1.

The test waveform would be used for the effects described in the parentheses.

Deviations or interpretations should be referred to the Lightning Protection Committee.

Low Level Component and Subsystem Level Testing

Currents and voltages induced in cables may be either of a damped oscillatory nature, similar to that shown in the a portion of figure 7-1, or of an exponential nature, similar to that shown in the b portion of figure 7-1. Test currents and voltages induced into cables by transformer coupling techniques will generally include a backswing. The backswing may generally be ignored if its amplitude is less than 25 percent of the initial amplitude. The choice of waveform and defining parameters of the waveform must be made as part of the process of assigning transient design levels and the conduct of transient proof tests.

OTHER WAVEFORM DEFINITIONS

Some terms frequently used in reference to simulated lightning test waveforms follow. These are excerpts from the USA and IEEE Standard "Techniques for Dielectric Tests." USA.C68.1 and IEEE No. 4 define waveform parameters for the last three non-oscillatory components. The paragraph numbers refer to the USA and IEEE document numbers.

Impulse Currents

5B.1.3 Virtual Front Time. The virtual front time t_1 is defined as 1.25 times the interval between the instants when the impulse current is 10 percent and 90 percent of the peak value.

If oscillations are present on the front, the 10 percent and 90 percent values should be derived from the mean curve drawn through these oscillations.

5B.1.4 Virtual Origin O_1. The virtual origin O_1 of an impulse is defined as the instant preceding that corresponding to the time at which the current is 10 percent of the peak value by 0.1 t_2.

For oscillograms having linear time sweeps, this is the intersection with the abscissa of a straight line drawn through the 10 percent and 90 percent reference points on the front.

5B1.5 Virtual Time to Half Value t_2. The virtual time to half value is the time interval between the virtual origin and the instant on the tail, where the current has decreased to half the peak value.

5B.1.6 Virtual Duration of a Rectangular Impulse Current. The virtual duration of a rectangular impulse current is defined by the time during which the current is greater than 90 percent of the peak value.

Impulse Voltages

5A.1.1 Full-Impulse Voltage. A full-impulse voltage is ideally an aperiodic transient voltage that rises rapidly to a maximum value and falls usually less rapidly to zero.

5A.1.3 Peak Value, Alternatively Virtual Peak Value. The peak value is normally the maximum value. With some test circuits, oscillations or overshoot may be present on the voltage. If the amplitude of the oscillations is not greater than 5 percent of the peak value and the frequency is at least 0.5 megahertz, or alternatively, if the amplitude of the overshoot is not greater than 5 percent of the peak value and the duration not longer than 1 microsecond, then for the purpose of measurement a mean curve may be drawn, the maximum amplitude of which is defined as the peak value.

5A.1.4 Virtual Front time t. The virtual front time t is defined as 1.67 times the time interval t between the instants when the impulse is 30 percent and 90 percent of the peak value. If oscillations are present on the front, the mean curve should be drawn through the oscillations.

5A.1.5 Virtual Origin 0 of an Impulse. The virtual origin 0 of an impulse is defined as the instant preceding that corresponding to point A by a time 0.3 t. For oscillograms having linear time sweeps, this is the intersection with the abscissa of a straight line drawn through the reference points on the front.

5A.1.6 Virtual rate of Rise (RR) of the Front. The virtual rate of rise (RR) of the front is the quotient of the peak value and the virtual front time.

5A.1.7 Virtual Time to Half Value t. The virtual time to half value t of an impulse is the time interval between the virtual origin and the instant on the tail, when the voltage has decreased to half peak value.

Further information may be obtained from the following sources:

1. Standard "Techniques for Dielectric Tests" USA C68.1, IEEE No. 4, 1968 IEEE - 3115 East 47th Street, New York, N.Y. 10017.

2. J. D. Robb, R. F. Huber and C. J. Kawiecki, "Lightning Test Facilities and Measurements Techniques," USAF Avionics Laboratories, Wright-Patterson AFB, Ohio, Proceedings, 1970 Lightning and Static Electric Conference, December, 1970, San Diego, California.

3. R. H. Evans and J. Phillpott, "Lightning Simulation and Testing in Relation to Specification MIL-B-5087-B," Proceedings, 1972 Lightning and Static Electricity Conference, December 12, 1972, Las Vegas, Nevada.

APPENDIX F

MAGNETIC FIELDS, CONDUCTOR CURRENTS, AND CONDUCTOR VOLTAGES WITHIN DIFFERENT ZONES OF THE SPACE SHUTTLE

A lightning strike to the Space Shuttle will produce electromagnetic fields within the vehicle. The magnitude and waveshape of these fields will be dependent upon the current amplitude and waveshape of the lightning strike, the point on the vehicle that is struck, and upon the degree of electromagnetic shielding offered by the vehicle. External to the vehicle, there will be both intense electric and magnetic fields, but inside the vehicle the magnetic fields will predominate. The electric fields will be negligible except near apertures. The magnetic fields will also be high near apertures.

The magnetic fields, if they pass between a cable and the vehicle structure, will induce a common-mode voltage between the conductors of the cable and the vehicle structure. The voltage will depend upon the magnetic field intensity, the rate of change of that magnetic field, the cable length, the spacing between the cable and vehicle structure, and the shielding of the cable. This induced voltage may either appear in the form of a voltage across open contacts, or may cause a current to circulate through cable shields or low-impedance input circuits. Whether or not damage or malfunction occurs depends on the amplitude and waveshape of these voltages and currents, and on the type of device upon which the voltage appears or through which the currents circulate. Evaluation of these fields, voltages, currents, and effects is a difficult and complex task, and if pursued rigorously would be quite expensive and time consuming.

In order that initial specifications regarding avionics equipment for the Space Shuttle may be defined, an analysis has been made of the expected magnetic fields within different regions of the Orbiter and of the open-circuit voltage or short-circuit current that may be induced by such fields. These analyses are not rigorous, but do reflect the collective judgment of several individuals with considerable experience in aircraft and electromagnetic shielding. They are believed to be conservative, but representative of the effects produced by severe lightning strikes. If application of these data indicate a severe compatibility problem leading to severe cost or weight penalties, further analysis is warranted.

Figure F-1 shows the different regions within the structure that were or will be considered in this analysis. These are:

Zone 1 - flight deck

Zone 2 - center equipment bay

Zone 3 - lower equipment bay

Zone 4 - forward top

Zone 5 - forward center

Zone 6 - payload bay

Zone 7 - aft equipment bay

Zone 8 - engine compartment

Zone 9 - vertical stabilizer

Zone 10 - wing

No consideration has yet been given in this analysis to equipment within the vertical stabilizer (zone 9) or within the wings (zone 10).

The magnetic fields within the structure will be different depending upon the point at which the lightning arc attaches to the structure, and upon the mechanism by which the magnetic fields couple to the inside of the structure. Coupling may be either through apertures or by diffusion through the metal skin. An example of an important aperture is through the windshield into the flight deck, Zone 1. This aperture coupling is particularly important for a strike near the top of the windshield, shown as strike B in figure F-1.

The fields in the different zones can be represented as the direct superposition of two components, one due to aperture coupling, component A, and one due to diffusion coupling, component B. Component A has a waveform the same as that of the incident lightning current while the component B has a waveshape with longer rise and fall times than the incident lightning current. The waveshape of component A is the same for the different zones. This is also true for the waveshape of component B. The amplitudes of the two components are not assumed to be related. The waveshapes of the two components are shown in figure F-2, while the amplitudes are shown in table F-I.

If only common-mode voltages are considered and only cable systems short enough that transmission line effects need not be considered, the induced voltage will be

$$e = \frac{d\phi}{dt} = \mu_o \; A \frac{dH}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1)$$

where A = area of the loop involved - meter^2

$\mu_o = 4\pi \times 10^{-7}$ - henry/meter (permeability of free space)

ϕ = total flux linked in webers

H = magnetic field intensity in amperes/meter

t = seconds

e = volts

expressed in inch units

$$e = 8.11 \times 10^{-10} \times \ell \times h \frac{dH}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2)$$

where ℓ = length of cable bundle - inches

h = height above ground plane - inches

H = amperes/meter

t = seconds

It must be emphasized that the voltage so calculated is that existing between the entire group of conductors (comprising the cable) and the vehicle structure. The voltage will divide between the loads at the ends of the cable inversely as the impedance of the loads. For worst case analysis, consider one end of the cable grounded with the other end open circuited. All the voltage so developed will appear at the open-circuit end of the cable.

Line-to-line or circuit voltages will be less, generally by a factor of 10 to 100 or 20 to 40 dB down from the common-mode voltages because individual conductors are usually close together and are often twisted, thus reducing the total loop area.

The maximum cable current is that which flows when both ends of the cable are connected to the vehicle structure through a low or zero impedance. Such an impedance may be an overall shield grounded at each end or it may be a group of semiconductor circuits, each having low input impedance. In the first case, the current will flow on the overall shield with the current on the input circuits determined by the shielding properties of the shield. In the second case, the current will flow directly through the input semiconductors and their bias sources.

The short circuit current that flows may be determined from the familiar expression

$$e = L \frac{di}{dt} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad 3)$$

$$\text{whence } i = \frac{1}{L} \int e dt \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad 4)$$

i = amperes

L = self-inductance of cable in henries

e = open circuit induced voltage in volts

t = time in seconds

Cable inductance may be estimated from the expression

$$L = 2 \times 10^{-7} \log_e \frac{4h}{d} \text{ henries/meter} \quad \ldots \ldots \ldots \quad 5)$$

$$\text{or } 5.08 \times 10^{-9} \log_e \frac{4h}{d} \text{ henries/inch} \quad \ldots \ldots \ldots \quad 6)$$

where h = height above a ground plane

d = conductor diameter

The induced voltage, e, which drives the current is proportional to the cable height, but the cable inductance which impedes the flow of current is proportional to the logarithm of the cable height.

Cable voltages and currents calculated as above are given in table F-II. Worst case external cable currents were computed for the external tank (300 amperes) and for each of the solid rocket booster cables (700 amperes).

TABLE F-1.- MAGNETIC FIELDS IN DIFFERENT ZONES OF THE STRUCTURE

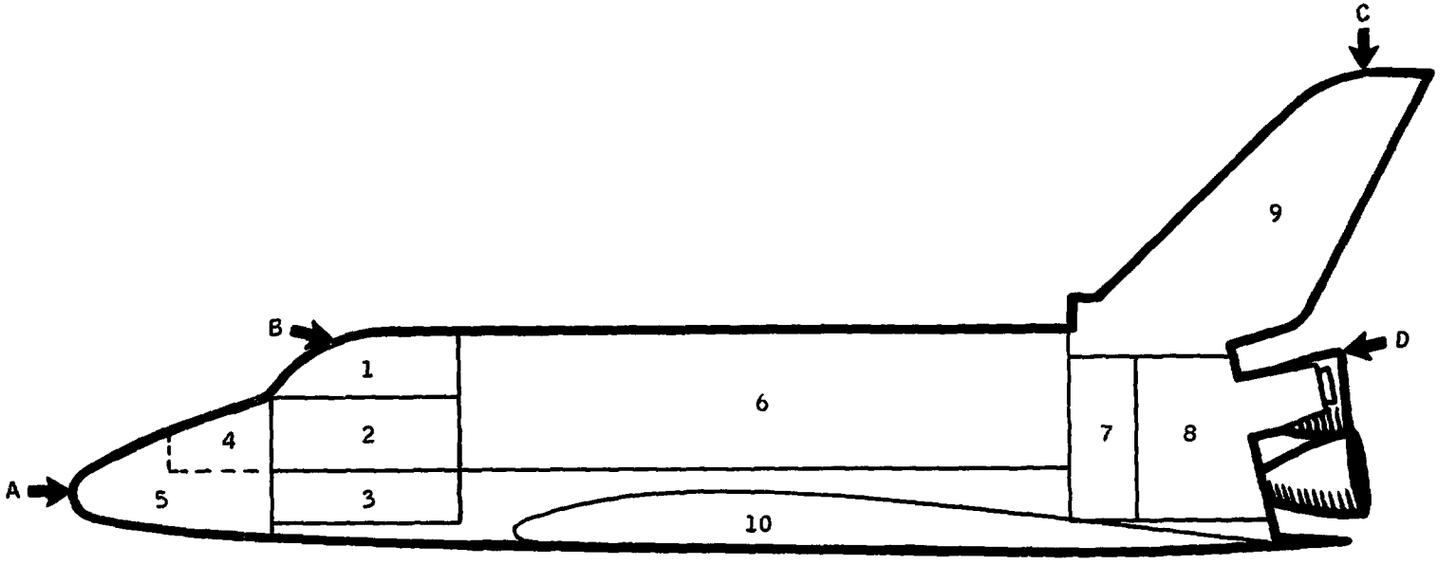
Zone	Aperture coupling A-component, amperes/meter	Diffusion coupling B-component, amperes/meter
1	1000	30
2	10	10
3	1	10
4	1000	1000
5	300	300
6	100	10
7	10	10
8	100	100
9	To be determined	To be determined
10	To be determined	To be determined

TABLE F-II.- OPEN CIRCUIT VOLTAGE AND SHORT CIRCUIT CABLE CURRENT IN THE VARIOUS ZONES

Zone	h = 1 inch		h = 2 inches		h = 5 inches		h = 10 inches	
	Voltage volts	Current amperes	Voltage volts	Current amperes	Voltage volts	Current amperes	Voltage volts	Current amperes
1	40.6	89.1	81.1	121	203	219	406	365
2	0.41	0.91	0.82	1.22	2.0	2.21	4.1	3.68
3	0.043	0.89	0.087	1.21	0.22	2.19	0.43	3.65
4	40.8	91.6	81.6	122	204.1	221	408	368
5	12.2	26.9	24.5	36.6	61.2	66.2	122.3	136
6	To be determined							
7	0.41	0.91	0.82	1.22	2.0	2.21	4.1	3.68
8	4.1	9.16	8.2	12.2	20	22.1	41	36.8
9	To be determined							
10	To be determined							

All values based on cable length = 100 inches.

For other lengths scale proportionately.

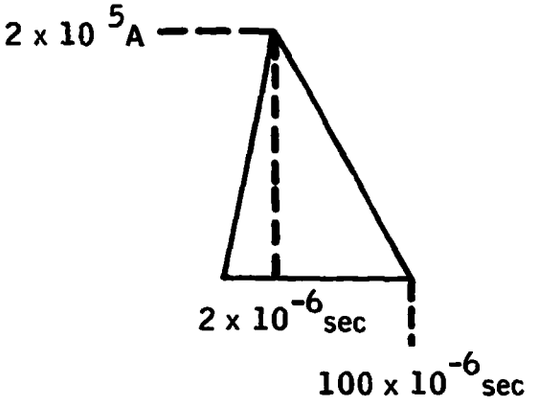


A through D - Most probable lightning arc entry and exit points

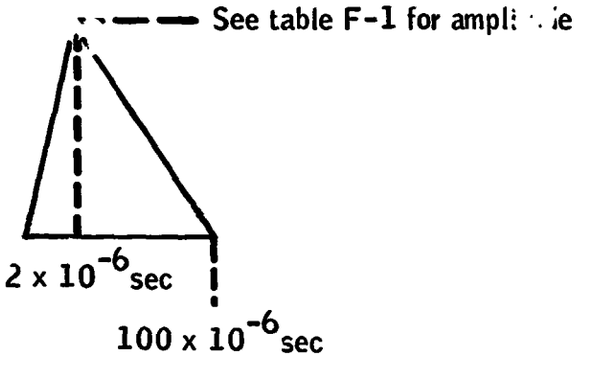
Shuttle zones

1	Flight deck	6	Payload bay
2	Center equipment bay	7	Aft equipment bay
3	Lower equipment bay	8	Engine compartment
4	Forward top	9	Vertical stabilizer
5	Forward Center	10	Wing

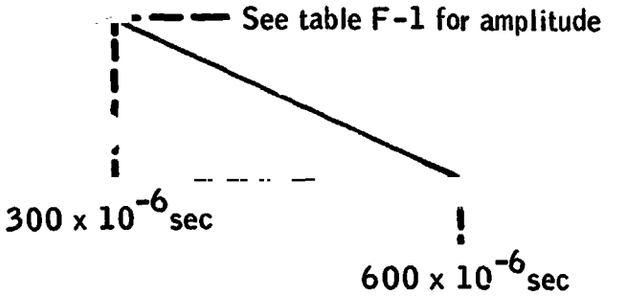
Figure F-1.- Shielded zones within the orbiter structure.



(a) Lightning current



(b) Aperture coupled field, A-component



(c) Diffusion coupled field, B-component

Figure F-2.- Waveforms of aperture and diffusion coupled magnetic fields.